

Good Morning ladies and gentlemen, I will be spending the next few minutes describing the exciting field of Spintronics.

Spin Electronics or Spintronics as I have affectionately named it has the potential to create a new paradigm in electronics for this new 21st century.

This new electronics will be based on the spin degree of freedom of the electron rather than the charge, as is the case for all conventional electronics.

Conventional electronics uses the charge of the electron to carry out all of the functions that we associate with our high tech world.

From light bulbs to computers, it is the flow and control of electron charge that is responsible for the operation of the devices.

As Dirac pointed out early in the 20th Century, electrons also have an unusual characteristic called spin.

The electron spin is quantized in units of angular momentum and is generally thought of as being either spin up or spin down.

Up until recently the spin of the electron has been ignored, although it represents a powerful new way to build electronics devices - spintronics.

Instead of controlling the flow of charge, spintronic devices operate by manipulating the direction of the spin and the coupling between spins.

The potential for spintronics is not only for very high speed, very low power systems for computation and communication but for some applications we have not even conceived of today.

This quote you see in front of you was part of a challenge that Richard Feynman presented to his audience at the American Physical Society Meeting in 1959.

He challenged his audience to " build computers with wires no wider than 100 atoms, a microscope that could view individual atoms, machines that could manipulate atoms 1 by 1, and circuits involving quantized energy levels or the interactions of quantized spins" Prof. Feynman was very prophetic in these challenges since they have mostly been achieved-except the last one which we hope make a reality through this new DARPA project.

By the way, Feynman offered prizes for those they were able to meet some of his challenges, of course DARPA has it's own way of rewarding innovation-- funding.

Here is where we are today in spintronics.

Spintronics essentially started in 1988 with the discovery in magnetic multilayers of giant magnetoresistance or GMR as it is commonly referred to.

GMR can be simply described as the large change in resistance of a sandwich of two magnetic films separated by a non-magnetic spacer.

If the two magnetic films are magnetized in the same direction than the sandwich has very low resistance.

If the magnetic layers are magnetized in opposite directions than the sandwich has much higher resistance.

The magnetic layers polarize the electrons in a similar fashion to an optical polarizer and just as the amount of light going through two polarizers is controlled by the relative polarization direction, the current through the magnetic sandwich is controlled by the relative direction of magnetization in the two magnetic layers.

Although GMR was only discovered only 12 years ago, it was brought to the marketplace 10 years later in 1998 when IBM introduced a hard disk drive that had a GMR read head sensor.

This revolutionized the \$100B hard drive industry.

All of the manufacturers had to adopt this technology or fail.

Magneto-resistive devices for non-volatile, high density, high-speed random access memory will soon be introduced into the DOD and Commercial marketplace and compete for a significant fraction of that >\$100B market. Highly sensitive magnetoresistive sensors are already competing for parts of the automotive and other sensor markets today.

Over the past two years there have been some major discoveries that will revolutionize the electronics of the future.

A very long lived collective and coherent spin state has been formed by shining circularly polarized light on garden-variety semiconductors like silicon, gallium arsenide, gallium nitride etc.

In addition, ferromagnetism was discovered in GaMnAs at 120K which opens the door to even higher temperature ferromagnetic semiconductors.

The combination of these discoveries will make possible new paradigms of spintronic devices for opto-electronics and very high performance logic, memory and perhaps eventually quantum computation and communication based on more traditional materials than the spintronic devices that I discussed previously- for example, like the ones I described for the GMR read head sensors.

This is a pictorial representation of some of the seminal work in semiconductor spintronics that I just mentioned.

A beam of circularly polarized light illuminates a semiconductor surface and generates a puddle of coherent spin polarized electrons.

These electrons have their phase coherent with the phase of the optical excitation that created them.

If this puddle is subjected to a very weak electric field, it moves through the semiconductor.

At some later time, a short distance away, another beam of light can extract information about this spin state.

Coherence has been observed to persist over 100's of nanoseconds and for distances of 100's of microns.

This observation indicates that this coherent state can be utilized to carry and process the spin information which may be the basis for a new paradigm in electronics I just mentioned.

The same optical experiment shown in the upper part of the slide on performed on a nanoparticle quantum dot indicates that a coherent spin state consisting of a very few electrons can persist for long times in these nanostructure quantum dots even at room temperature.

There are many avenues of research that have to be explored in order to turn scientific discovery into the rudiments of a completely new technology.

Since this field is very new there needs to be much work to understand all of the properties of the spin state of the electron in semiconductors.

Of particular importance is understanding how this coherent spin state propagates across boundaries between different semiconductors.

Eventually, we will need to address the various potential applications of this new physics by demonstrating prototype optical devices like switches and encoders and all electronic devices like spin transistors. Finally, we must develop the ability to understand and manipulate the spin state to perform quantum computation and communication and build what may become the first Quantum Internet

One of the major challenges of semiconductor spintronics is the ability to transfer spin information across boundaries between different semiconductors.

This recent experiment done at the University of California Santa Barbara illustrates that in the case of a GaAs/ZnSe boundary, this process proceeds without much difficulty and spin dependent information is transferred across quickly and with high fidelity.

This is another seminal experiment that is paving the way to a more complete understanding of the spin dependent properties of semiconductors.

Using very clever two frequency optical pump-probe techniques similar to those described earlier for determining the spin coherence in a single semiconductor, the team at the University of California Santa Barbara have probed the motion of the coherent puddle of spins as it propagates across the boundary and found that the boundary did not cause the coherence to decay.

In fact the lifetime increased as the puddle moved from the GaAs into the ZnSe.

There are many potential devices and technologies that may be significantly impacted by semiconductor spintronics.

There are three areas that will definitely be impacted.

The first is what I call Quantum Spin Electronics and this area refers to devices that are more conventional but can be enhanced by adding the spin degree of freedom to their operation.

They include spin transistors, spin-LEDs, spin-resonant tunneling diodes and perhaps even spin lasers.

The second category of Coherent Spin Electronics takes advantage of the special coherence that was discovered very recently.

In this case the devices that we might build are optical switches, encoders, decoders, modulators, phase logic and perhaps phase memory.

The final category of Quantum Information processing involves using the coherent spin state to perform quantum mechanical operations for the exotic field of quantum computing and quantum communication perhaps enabling something like a quantum internet in the not too distant future.

As I just indicated, the most interesting application of spintronics may be in the area of quantum information science and technology where the spin is almost the perfect quantum bit or qubit.

The power of quantum computing is illustrated in the fact that a quantum state can be prepared by superposing two other quantum states in a linear combination.

Thus, even though the spin of an electron only has two states - up and down, any spin direction can be quantum statistically represented as a linear combination of up and down.

For example, a state pointing horizontally can be represented by a quantum spin state that has a 50% probability of being up and a 50% probability of being down.

However these quantum statistical states can interact with each other and interfere so that in the end there is a definite rather than a statistical result.

This interaction makes using qubits a highly parallel process and n qubits can, in fact, represent 2^n classical bits in some special cases.

The result of this parallelism is a dramatic speedup in performing certain important operations like finding the prime factors of a large number.

The power of this is illustrated on the next slide.

Here we show a comparison of a classical "Intel" processor with a quantum mechanical "quintel" processor.

For certain calculations that find global properties of functions like factoring and discrete optimization the speedup for a quantum processor is very dramatic.

It is exponential for factoring and quadratic for optimization.

For these operations a 30-qubit quantum processor can perform the same calculation as a 10 million bit classical computer.

In fact a 400-bit number cannot be reasonably factored on a conventional computer but it theoretically can be factored in less than an hour on a quantum computer.

The challenge is to build such a computer.

That my friends is for you to do.

In fact there are some very good ideas that have been proposed recently. One of which is illustrated on the next slide.

Here is an illustration of proposed solid-state method to build such a quantum processor using a new type of transistor called a spin resonance transistor.

This device was proposed by a team from UCLA.

The two key features that are required for such a device. The first is that the quantum coherent state not be perturbed by the environment and decohere.

Thus the characteristics of this device must have a long decoherence time.

The other important characteristic of such a device is that the time to perform a quantum operation be very short, especially compared to the decoherence time - again this device should meet this challenge as well.

This device works by using the electron spin of an impurity atom as the qubit and manipulating it by moving into regions with different spin resonance frequencies using gates.

This device will be a challenge to build but is certainly feasible using what we know of semiconductor processing.

By the way, we expect a new DARPA project entitled Quantum Information Science and Technology or QuIST to be initiated in fiscal year 2001.

This project will explore all aspects of this exciting new field and I encourage you to pay attention to the announcements in Commerce and Business Daily.

In fact, a workshop in conjunction with this project will be held in Greenbelt MD, October 23 and 24th. More information can be found on the DARPA web site.

I am about done.

I would like to invite all of you who are interested in this program to contact me to discuss it further.

Unfortunately there is not much time left at this meeting but I can be reached by e- mail at swolf@darpa.mil.

This ends my little spin into the future.

I hope there are spins in your future as well.